

ABSTRACT

Lecture for IEEE Hydrogen Economy Forum
Washington DC 19-20 April 2004

The fuel cell uses a catalyzed reaction between a fuel and an oxidizer to directly produce electricity. Its high theoretical efficiency and low temperature operation made it a subject of much study upon its invention ca. 1900, but its relatively high life cycle costs kept it as "solution in search of a problem" for its first half century. The first problem for which fuel cells presented a cost effective solution was, starting in the 1960's, that of a power source for NASA's manned spacecraft. NASA thus invested, and continues to invest, in the development of fuel cell power plants for this application. However, starting in the mid-1990's, prospective environmental regulations have driven increased governmental and industrial interest in "green power" and the "Hydrogen Economy." This has in turn stimulated greatly increased investment in fuel cell development for a variety of terrestrial applications. This investment is bringing about notable advances in fuel cell technology, but these advances are often in directions quite different from those needed for NASA spacecraft applications. This environment thus presents both opportunities and challenges for NASA's manned space program.

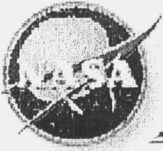


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The Development of Fuel Cell Technology for Electric Power Generation

From Spacecraft Applications to the Hydrogen Economy

John H. Scott
EP5/Power Systems Branch
NASA Lyndon B. Johnson Space Center
(281) 483-3136

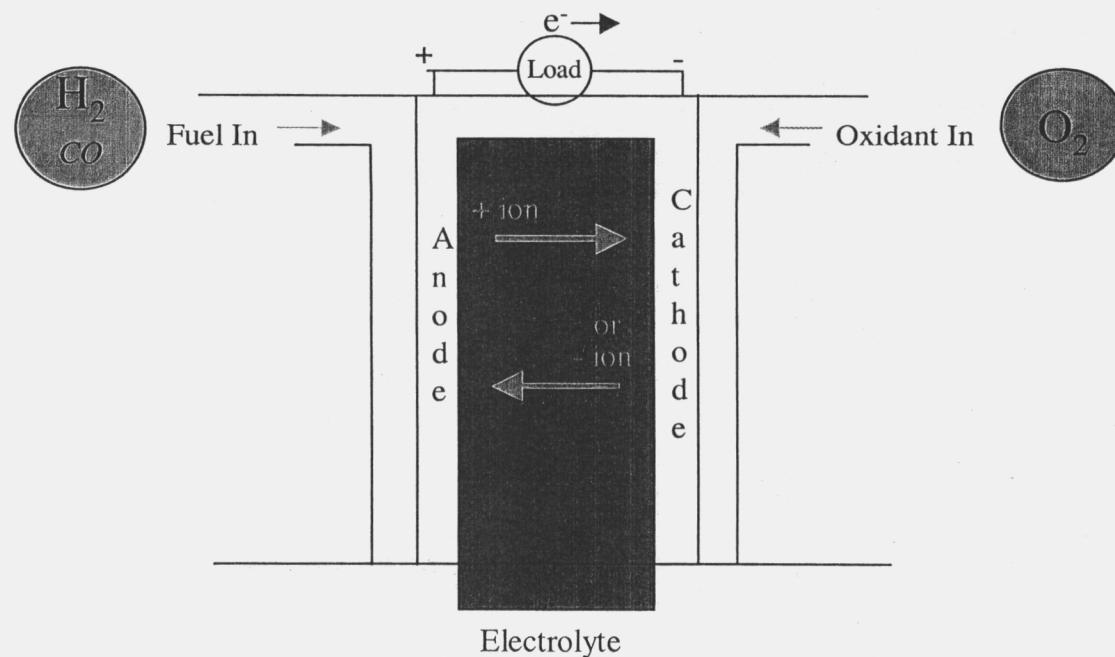
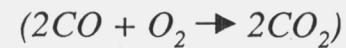


Fuel Cell Fundamentals



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Cell Electrochemical Reaction



Nernst Equation (*Hydrogen Anode*): $E = E^0 + (RT/2\mathcal{F})\ln(P_{\text{H}_2}/P_{\text{H}_2\text{O}}) + (RT/2\mathcal{F})\ln[(P_{\text{O}_2})^{1/2}]$

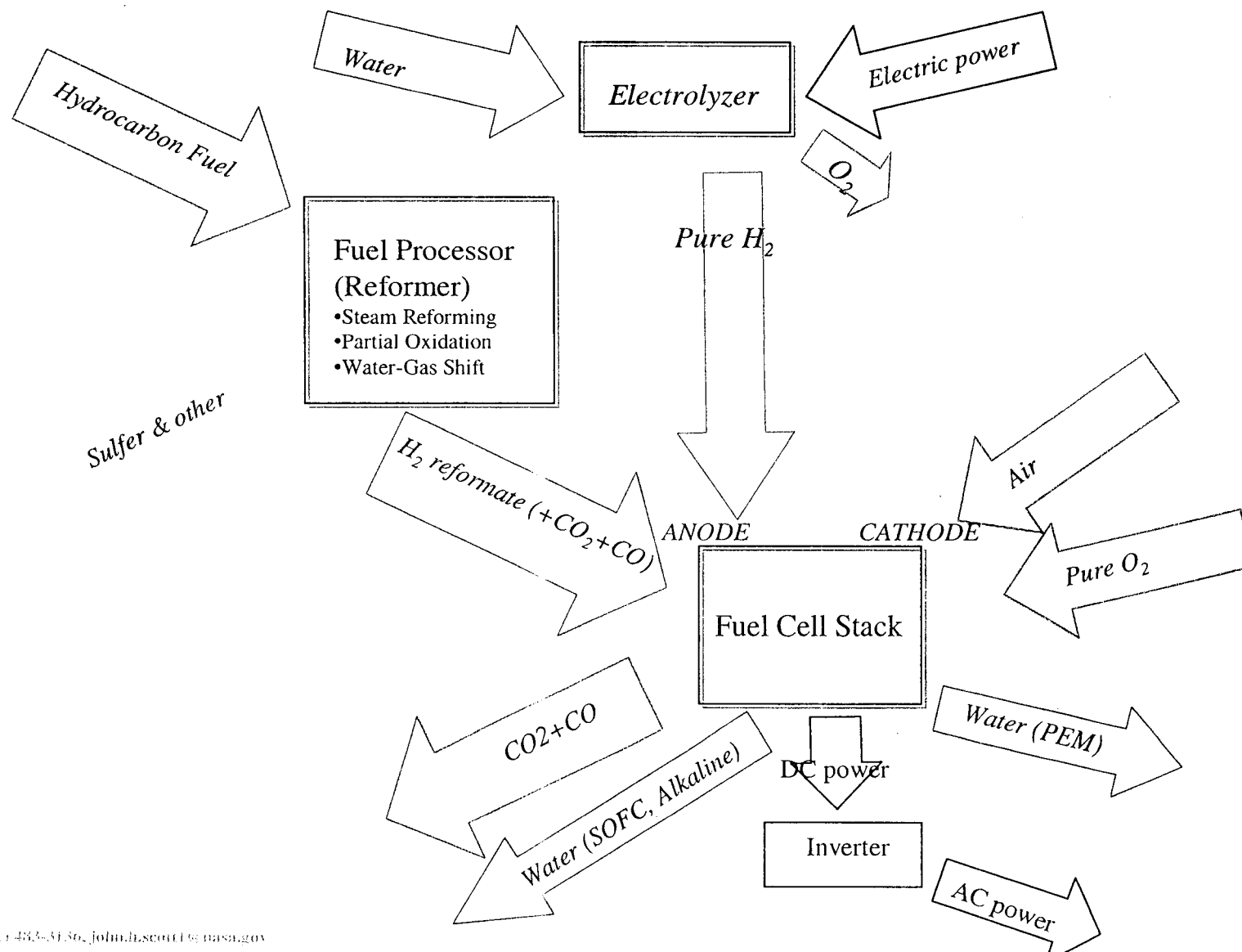


Fuel Cell Fundamentals



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Power Plant Elements





Fuel Cell Fundamentals



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Basic Fuel Cell Power Plant Characteristics

Chemistry	Alkaline	PEM	SOFC
Electrolyte	Concentrated KOH in asbestos matrix	Ion exchange membrane	Ceramic - Solid nonporous metal oxide ($Y_2O_3-ZrO_3$)
Catalyst	Pt	Pt	Ni-ZrO ₃ Co-ZrO ₃ Sr-LaMnO ₃
Fuel Capability	Pure H ₂	H ₂ from clean reformat	CO and H ₂ from dirty reformat
Operating Temperature	~90 C	~80 C	800-1000 C
Water Production	Fuel side (two phase)	Oxidant side (two phase)	Fuel side (vapor)
Operating Life Drivers	Operating Time	Humidity Control	Thermal Cycles
Thermodynamic Efficiency (Fuel Tank to AC Power Bus)	50-55%	30-40%	45-60%



Design Drivers for Electric Power Systems



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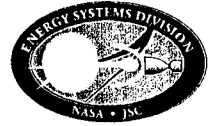
Commercial/Military Power Systems:

- Emissions Reduction (NO_x , CO_x , noise)
- Specific Power (kW/kg)
- Production cost ($\text{\$/kW}$)

Constraint: Public Safety



Design Drivers for Electric Power Systems



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Spacecraft Power Systems:

- Specific Energy (kWh/kg)
- Specific Energy (kWh/kg)
- Specific Energy (kWh/kg)

Constraint: Mission Reliability



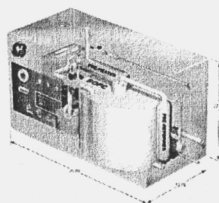
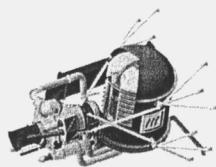
Fuel Cell Development Roadmaps



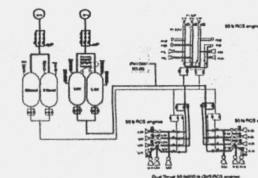
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Transportation



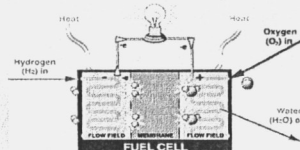
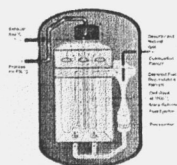
Distributed Generation



Integrated
Regenerative
Systems
(2000+)

Solid Oxide

PEM



Aeronautics



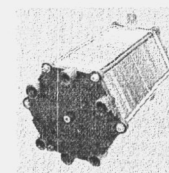
DOT



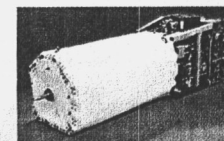
DOD



DOE



Advanced
PEM
(late 1990's)



Shuttle
Alkaline
(1970's)

"Hydrogen
Economy"

"Green Power"

EPA United States
Environmental Protection Agency
mid-1990's



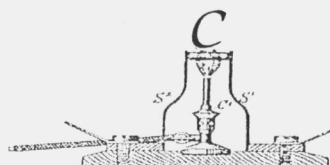
Apollo Alkaline
(late 1960's)



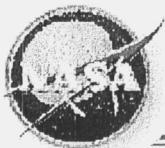
Gemini PEM
(early 1960's)



Spacecraft



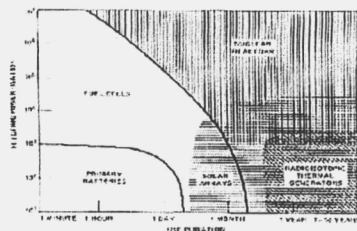
W. Nernst 1899



NASA Spacecraft Fuel Cell Technology Roadmap



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Photovoltaics

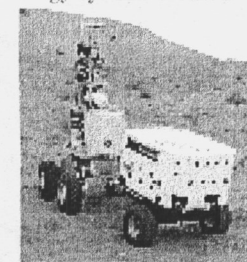
Batteries

Nuclear



Planetary Rovers:

- PEM fuel cell power plant
- Steam reforming of fuel from planetary resources
 - Methane (CH_4), or
 - Ethanol ($\text{C}_2\text{H}_5\text{OH}$)
 - Methanol (CH_3OH)
- Oxidant (O_2) from planetary resources (*e.g.*, *electrolysis*)



Power System Mission Drivers

- Duration?
- Solar availability?
 - Flux?
 - Surface area?
- Heat rejection capability?
- Launch mass limits?

Fuel Cell Requirements:

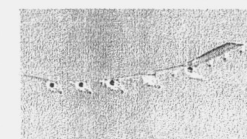
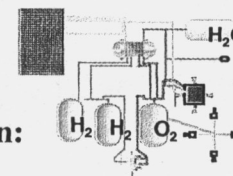
- Pure O_2 oxidant stream
- Load following (*e.g.* 6:1 in 200 ms)

Development toward improved:

- Fluid commonality with propulsion, life support, thermal control, etc
- Mission reliability
- Life cycle cost
- Power/energy density

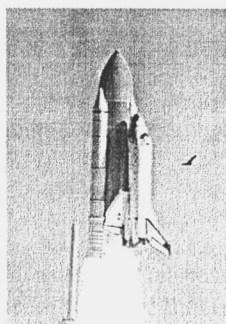
Advanced Exploration:

- Gravity independence
- Regenerative fuel cells
- Electrolysers
- H_2O propulsion



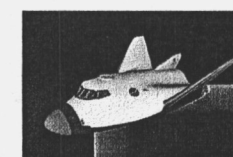
1970's Space Shuttle

- Alkaline fuel cell power plant
- Gravity-independent water management (*0-g, multi-g, vibration*)
- Full mission reactant storage
- Reactant grade O_2 (*supercritical*)
- Propulsion grade H_2 (*supercritical*)



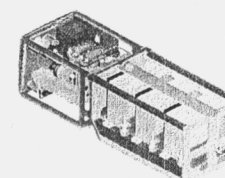
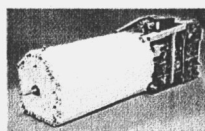
Next Generation Launch Technology and Crew Exploration Vehicle

- Proton Exchange Membrane (PEM) fuel cell power plant
- Gravity-independent water management (*0-g, multi-g, vibration*)
- Full mission reactant storage
- Propulsion grade O_2 (*liquid*)
- Propulsion grade H_2 (*supercritical*)



1990's Shuttle Upgrades

- Long Life Alkaline Fuel Cell



- H_2 reformed on-board (<10 ppm CO) from $\text{C}_2\text{H}_5\text{OH}$ fuel (*common fuel with propulsion*)



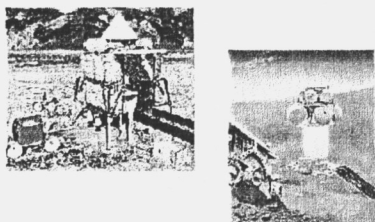
Fuel Cells for Planetary Exploration



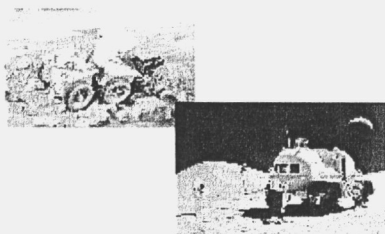
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Common Technologies & Fluids Maximizes Benefits, Flexibility, & Affordability

In-Situ Production Of Consumables for Propulsion, Power, & ECLSS



Fuel Cell Power for Rovers & EVA



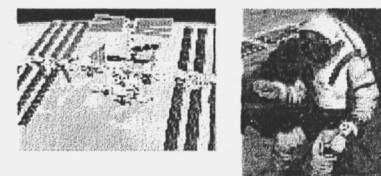
0-g & Reduced-g Propellant Transfer



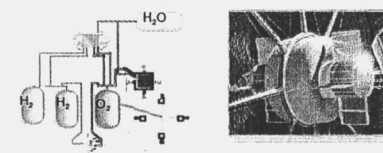
Core Technologies

- CO₂ & N₂ Acquisition & Separation
- Sabatier Reactor
- RWGS Reactor
- CO₂ Electrolysis
- Methane/HC Reforming
- H₂O Separators
- H₂O Electrolysis
- H₂O Storage
- Heat Exchangers
- Liquid Vaporizers
- O₂ & Fuel Storage (0-g & reduced-g)
- O₂ Feed & Transfer Lines
- O₂/Fuel Couplings
- Fuel Cells
- O₂/Fuel Igniters & Thrusters

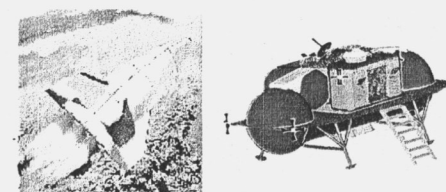
Life Support Systems for Habitats & EVA



Water – H₂/O₂ Based Propulsion



Non-Toxic O₂-Based Propulsion





The Primary Challenge for NASA's Space Program

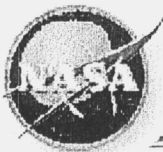


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New Space Exploration Vision

On January 14, 2004 the President announced a new vision for NASA

- Implement a sustained and affordable human and robotic program to explore the solar system and beyond;
- Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;
- Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and
- Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.



The Hydrogen Economy



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Toward a More Secure and
Cleaner Energy Future for America

NATIONAL HYDROGEN ENERGY ROADMAP

PRODUCTION • DELIVERY • STORAGE • CONVERSION
• APPLICATIONS • PUBLIC EDUCATION AND OUTREACH

Based on the results of the
National Hydrogen Energy Roadmap Workshop
Washington, DC
April 2-3, 2002

November 2002



United States Department of Energy

Toward a More Secure
and Cleaner Energy
Future for America

A NATIONAL VISION OF AMERICA'S TRANSITION TO A HYDROGEN ECONOMY — TO 2030 AND BEYOND

Based on the results of the
National Hydrogen Vision Meeting
Washington, DC
November 15-16, 2001

February 2002



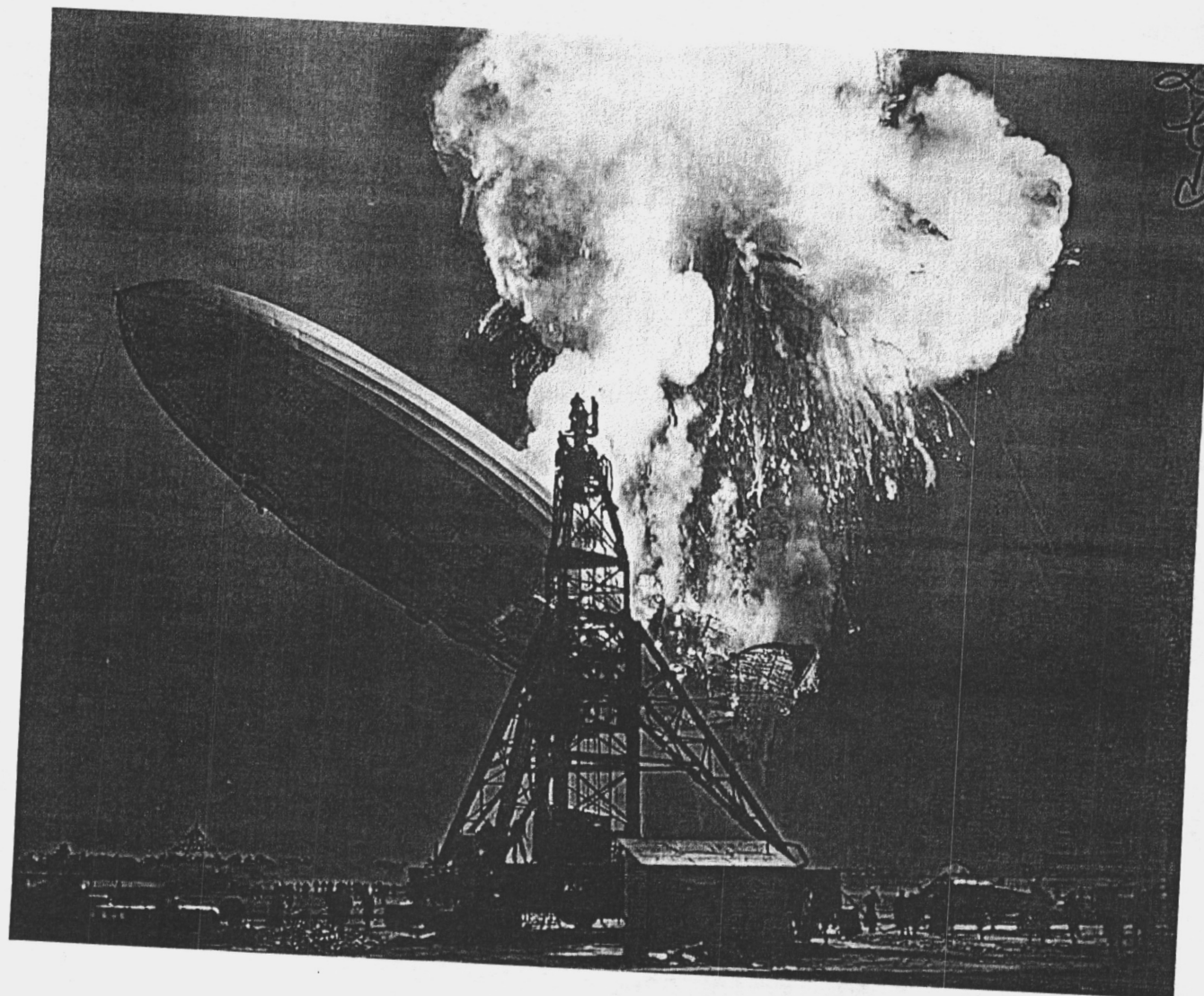
United States Department of Energy



The Major Challenge to the Hydrogen Economy

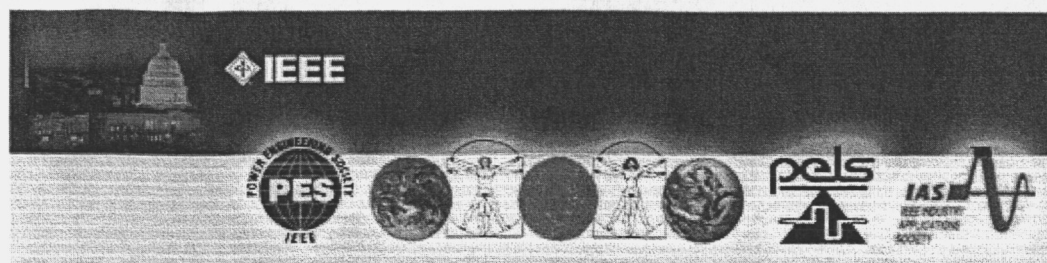


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John Scott, (281) 483-3136, john.h.scott1@nasa.gov

17 April 2004



- Home
- Mission Statement
- Registration
- Hotel & Travel Information
- Papers & Presentations
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- About IEEE

The Hydrogen Economy: its impact on the future of electricity

**19-20 April, 2004
JW Marriott Hotel, Washington, DC**

April 19, 2004

7:30-8:30am

Registration / Breakfast Snack Buffet

8:30-10:00am

Opening Session

- Greeting / Introductions
- Opening Presentation - What is a hydrogen economy?
- Keynote Address - Understanding the challenge:
The Honorable Robert Walker, Chairman, Wexler and Walker Public Policy Associates

10:00-10:30am

Break

10:30-12:15pm

Electric Energy and Hydrogen Links

- The Development of Fuel Cell Technology for Elec Power Generation: *John H. Scott*, NASA Lyndon B Johnson Space Center
- Lessons learned from Automotive Applications: TBD
- Fuel Cells for Stationary Power Application: TBD
- Sources of Hydrogen, How much is needed?: TBD
- Envisioning a Hydrogen Economy - Opportunities Electric Power: *Richard Scheer*, Energetics, Inc.
- Q&A Session

12:15-1:45pm

Lunch

1:45-3:30pm

Hydrogen Infrastructure - Challenges

- Large-Scale H₂ Production and Distribution: *Guenter Conzelmann*, Argonne National Laboratory
- Values of Electricity Storage in a Hydrogen Based Electrical System: *Ali Nourai*, AEP
- Q&A Session

3:15-3:45pm

Break

3:45-5:30pm

International Experience

- International Partnership for the Hydrogen Economy: *Robert K. Dixon*, Office of Energy

- Efficiency and Renewable Energy, US DOE
- European Union: TBD
- Hydrogen for Sustainable Growth and Hydrogen/Fuel Cell Projects in Japan: *Ken-ichiro Ota*, Yokohama National University
- Q&A Session

April 20, 2004

7:30-8:30am Breakfast Buffet / Late Registration

8:30-10:15am **Managing Major Technology Transition**

- A Technology Roadmap for Hydrogen: *Robert Schainker*, EPRI
- Economical Energy Conversion: TBD
- Commercialization Challenges: *David Parekh*, Georgia Tech
- Q&A Session

10:15-10:30am Break

10:30-12:00pm **Public and Private Decision Points**

- Formulating and Implementing Public Policy for Hydrogen: *Clint Andrews*, Rutgers University
- Lessons from the National Academy of Engineering Hydrogen Study: *Antonia Herzog*, Natural Resources Defense Council
- The "Value Proposition" of Hydrogen: *Scott Weiner Esq.*, Rutgers University
- Q&A Session

12:00-1:15pm Lunch

1:15-3:00pm **Closing Session**

- The Hydrogen Economy: The creation of the worldwide energy web and the redistribution of power on earth: *Jeremy Rifkin*, author of "Hydrogen Economy", President of the Foundation on Economic Trends
- Meeting Review Comments
- Closing Remarks
- Next Steps/Action Items

3:00pm Meeting Adjourned

 19-20 April, 2004; JW Marriott Hotel, Washington, DC

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